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PACKAGING SYSTEMS INCLUDING RECYCLING

Ecodesign of PVC packing tape using life cycle assessment

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Abstract
Purpose Polymer materials play an important role in the improvement and quality of life. However, due to their persistence in the environment, polymer materials may be harmful to the ecosystems. According to the European Directive on Packaging and Packaging Waste, management of these wastes should include prevention of their generation as a priority. The main motivation for employing ecodesign of a product is to reduce both raw material consumption and waste generation through a good initial design.
Methods In this study, life cycle assessment (LCA) was applied to the design of printed PVC plastic packing tape in order to reduce its environmental impact. LCA software GaBi4.4® was used to determine the PVC packing tape life cycle stage with the highest environmental impacts.
Results and discussion LCA results showed that PVC film manufacture was the stage with the highest impact. It was therefore reasonable to assume that packing tape manufactured with material other than PVC could have reduced environmental impact, and LCA was used to evaluate this hypothesis. When using Kraft paper or polypropylene plastic packing tape, the weighted impacts were reduced by 36.3 and 39.9 %, respectively.
Conclusions PVC plastic packing tape has been redesigned with the aim of reducing waste and raw material consumption. LCA results showed that a suitable option for reducing life cycle environmental impact is to use alternative film materials. Kraft paper and polypropylene plastic packing tape were found to give lower values of almost all environmental impact indexes and normalized and weighted impacts.

Keywords Ecodesign · Kraft paper · Life cycle assessment · Packing tape · Polypropylene · PVC

1 Introduction

Polymers have very important applications; however, due to their slow biodegradation rate, they present a danger to the environment. It is expected that during the beginning of the twenty-first century, there will be a two- to threefold increase in plastics consumption, particularly in the developing countries (Rudnik 2011). This increased use of plastics is accompanied by a rapid accumulation of solid waste and plastic litter, which have deleterious effects on the environment. General concern over these issues has resulted in the establishment of strategies aimed at minimizing the negative effect of the increasing production and consumption of polymer materials.

Municipal waste generation in the European Union (EU) has slowed down and stabilized in 2010 at about 520 kg per capita since 2002 due to current EU waste policy (Blumenthal 2011). EU directives about waste management are based on a concept known as the waste hierarchy. This means that ideally, waste should be first prevented and then reused, recycled and recovered as much as is feasible, with landfill being used as little as possible. According to the European Directive on Packaging and Packaging Waste, the management should consider as a priority the prevention of packaging waste and reuse, recycling and other forms of recovering packaging waste as additional principles (Directive 94/62/EC 1994). Prevention means the reduction of the quantity and harmfulness to

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the environment of materials and substances contained in packaging and all the wastes generated at the different life cycle stages.

The main objective of ecodesign is to reduce both contamination and raw material requirements through a good initial design of an industrial product. In this context, whether considering a redesign of an old industrial process or the development of a new design, it is first necessary to evaluate the environmental impacts of the various life cycle stages and to try to reduce the effects of the stage with the highest environmental impact. In order to improve product design, life cycle analysis (LCA) has been used to quantify the environmental impacts of the life cycle stages of the product. LCA is defined in ISO 14040 as the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle. Thus, LCA is a tool for the analysis of the environmental burden of products at all stages of their life cycles from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product to the management after it is discarded, either by reuse, recycling or final disposal (Guinée 2002). In recent years, LCA has found application in various industries such as, e.g. packaging (Suwanmanee et al. 2013), food (Amienyo et al. 2013), automobiles (Subic et al. 2010), electronics (Andrae and Andersen 2010), textiles (Gabarrell et al. 2012) and chemicals (Wernet et al. 2010).

In this study, the LCA software GaBi4.4® was applied to model the life cycle and ecodesign of printed plastic packing tapes. This software has a large database, which allows it to acquire inventory data with good precision; for this reason, it has been used in numerous and different LCA studies (Amienyo et al. 2013; Luz et al. 2010; Stichnothe and Schuchardt 2010). There are numerous databases available in LCA software tools including embedded databases such as SimaPro® and GaBi® databases. LCA has also been used in numerous ecodesign processes and implemented into several industry products (IHOBE 2000; Vezzoli and Manzini 2007; Wimmer et al. 2004, 2010).

The three main components of packing tape are film tape, adhesive and cardboard mandrel. Packing tapes are widely used for package closure of cardboard boxes. Regarding their environmental impact, some studies have only focused on their end-of-life stage (Putz 1997; Onusseit 2000). These studies attempted to reduce the end-of-life impact of the packing tapes with a correct design without affecting the recycling of corrugated cardboard containers (Onusseit 2012; Jensen 1997) and concluded that pressure-sensitive adhesive (PSA) plastic packing tapes do not cause problems in paper recycling. Later, plastic and adhesive from the packing tapes could be managed as municipal waste, or thermally treated, although in this case, plastic should not contain toxic compounds (Jensen 1997; ASTM 2011).

To our knowledge, there are no previous studies on LCA of packing tapes in the open literature. In this study, LCA was used to redesign printed PVC plastic packing tape in order to reduce the environmental impact of its entire life cycle.

2 Life cycle assessment of the product

In this study, the principles and guidelines of ISO14040:2006 and ISO14044:2006 have been followed (ISO14040:2006; ISO14044:2006).

2.1 Goal and scope definition

The goal of the LCA is to identify options for improving the environmental performance of the PVC packing tape. The results of this LCA will be used for product and process development. As there are no previous studies about packing tapes, LCA has to provide as much information as possible.

2.1.1 Functional unit

The main function of the product is providing an adherent and resistant surface for package closure of cardboard boxes. The functional unit of this study is 1,663 m^2 of packing tape surface, which is the total surface provided by one box of plastic printed packing tape sold by a printing company. One box contains 252 rolls of tape. The printing company receives a large roll of plastic tape that is divided into 24 smaller units which are then printed, packaged and delivered. Up to 10.5 large rolls of plastic tape are needed to produce 1,663 m^2 of packing tape surface.

2.1.2 System boundary

The limits of the study were the source of raw materials and the location of waste discharge, so the system boundary is from cradle to grave. Figure 1 shows the life cycle flow chart with all the material quantities for providing 1,663 m^2 of PVC packing tape surface, that is, the functional unit of the process.

2.1.3 LCIA methodology and types of impact

In order to cover all the environmental impacts of the product, and in accordance with the goal of getting as much information as possible, all the baseline impact categories (Guinée 2002) have been taken into account: climate change, depletion of abiotic resources, acidification, eutrophication, ecotoxicity (freshwater aquatic, marine aquatic, terrestrial), human toxicity, stratospheric ozone depletion and photooxidant formation.

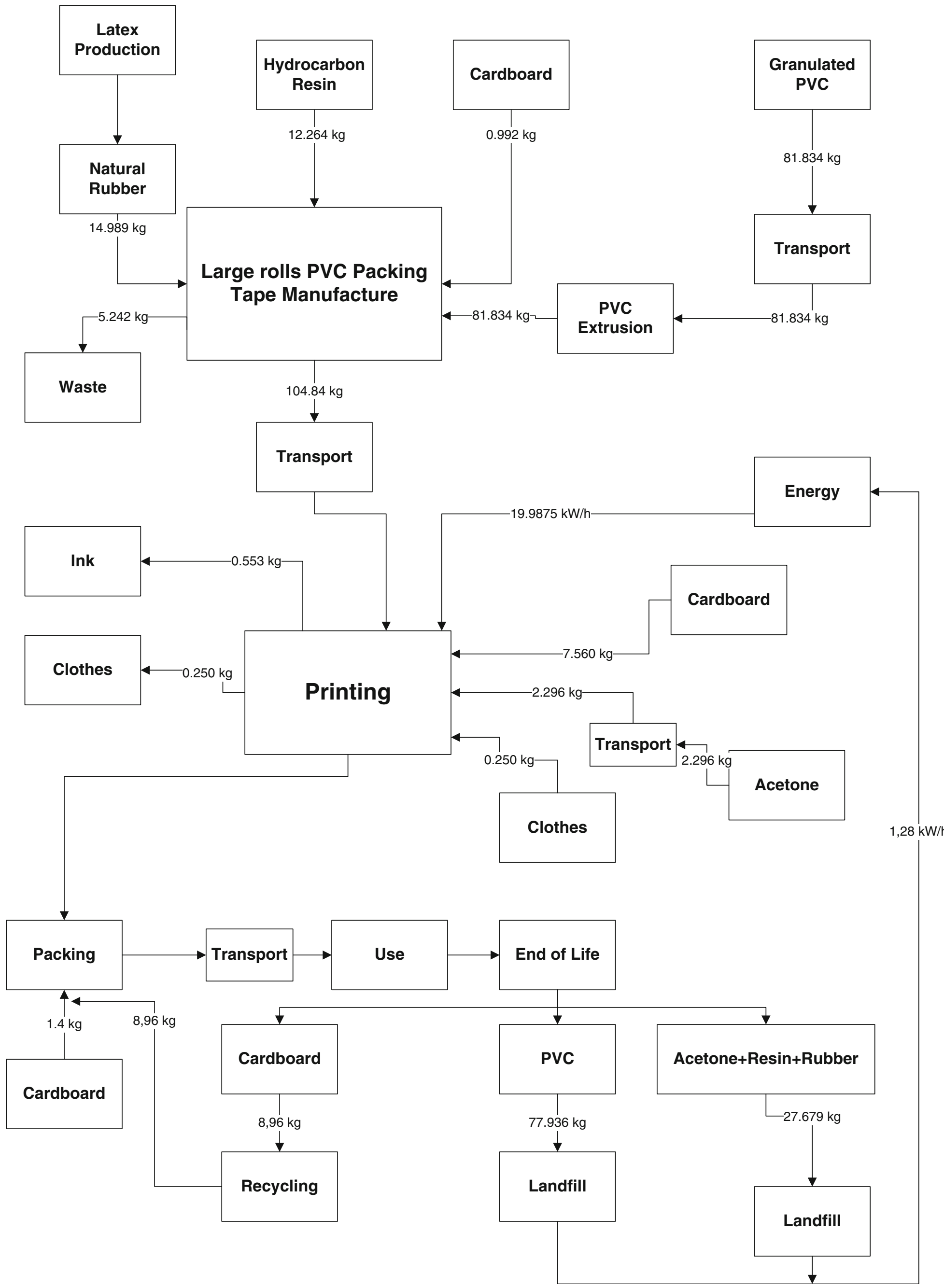


Fig. 1 Life cycle of the PVC packing tape

Baseline characterization methods developed by Guinée (2002) have been used for all selected categories in order to obtain the different 11 environmental impact indexes (EIIs) considered in this study.

– Climate change. Characterization model: developed by the Intergovernmental Panel on Climate Change defining the global warming potential of different greenhouse gases. Characterization factor: global warming potential (GWP) for a 100-year time horizon for each greenhouse gas emission to the air, EEI: GWP [in kilogram CO_2 eq.] (Solomon et al. 2007; Houghton et al. 2001).
– Depletion of fossil and mineral abiotic resources. Characterization model: a concentration-based reserves and rate of de-accumulation approach has been used. Abiotic depletion potential (ADP) fossil energy is calculated based on the total energy reserves and yearly extractions of fossil fuels (oil, coal and natural gas) as a total. Characterization factors: abiotic fossil depletion potential for each extraction of fossil fuels, EEI: ADP_{fossil} [in

megajoule eq.] (Guinée 2002), and abiotic mineral depletion potential for each extraction of mineral, EEI: $ADP_{mineral}$ [in kilogram Sb eq.] (van Oers et al. 2002).

- Acidification. Characterization model: RAINS10 model, developed at IIASA, that describes the fate and deposition of acidifying substances, adapted to LCA. Characterization factor: acidification potential for each acidifying emission to the air, EEI: AP [in kilogram SO_2 eq.] (Huijbregts 1999b; Heijungs et al. 1992; Hauschild and Wenzel 1998).
- Eutrophication. Characterization model: a stoichiometric procedure that identifies the equivalence between nitrogen and phosphorous for both terrestrial and aquatic systems. Characterization factor: eutrophication potential (EP) for each eutrophying emission to air, water and soil, EEI: EP [in kilogram PO_4^{3-} eq.] (Huijbregts 1999a; Heijungs et al. 1992; Hauschild and Wenzel 1998).
- Freshwater aquatic, marine aquatic and terrestrial ecotoxicity. Characterization model: USES 2.0 model developed at RIVM, describing fate, exposure and effects of toxic substances, adapted to LCA. Characterization factor: freshwater aquatic (FAETP), marine aquatic (MAETP) and terrestrial ecotoxicity potential (TETP) for each emission of a toxic substance to air, water and/or soil, EEIs: FAETP, MAETP and TETP [in kilogram dichlorobenzene (DCB) eq.] (Huijbregts 1999a; Huijbregts et al. 2001; Rosenbaum et al. 2008).
- Human toxicity. Characterization model: USES 2.0 model developed at RIVM, describing fate, exposure and effects of toxic substances, adapted to LCA. Characterization factor: human toxicity potential (HTP) for each emission of a toxic substance to air, water and/or soil, EEI: HTP [in kilogram DCB eq.] (Rosenbaum et al. 2008).
- Stratospheric ozone depletion. Characterization model: the model by the World Meteorological Organization, defining the ozone depletion potential of different gases. Characterization factor: ozone depletion potential (ODP) in the steady state for each emission to the air, EEI: ODP [in kilogram R11 eq.] (Daniel and Velders 2007).
- Photooxidant formation. Characterization model: UNECE Trajectory model. Characterization factor: photochemical ozone creation model for each emission of volatile organic compounds or carbon monoxide to the air, EEI: photochemical ozone creation potential (POCP) [kg C_2H_4 Eq.] (Derwent et al. 1998; Jenkin and Hayman 1999; Carter 1998).

2.1.4 Types and sources of data and data quality requirements

PVC packing tape dimensions, mandrel weights, energy and ink consumptions for the printing process and transport distances were obtained from the printing company. The supplier of the large rolls provided the film technical characteristics.

Environmental data regarding the consumption and emissions of each different material and energy production were obtained from the GaBi4.4® professional databases. Table 1 shows the life cycle inventory (LCI) sources used in this study.

All data collected meet the following requirements: time-related coverage, precision and completeness. Regarding the uncertainty of the information, some assumptions have had to be made (see “Inventory analysis” section) and checked by sensitivity analysis in the interpretation step. In order to check their quality, a data quality analysis has been done, and the following were the results obtained: 5.7 % of the data were measured, 22.3 % calculated, 47.6 % obtained from literature, 12.5 % estimated, and 11.9 % not described.

2.2 Inventory analysis

Table 2 shows the main characteristics of the packing tape. Dimensions of the PVC film were: length 132 m, width 0.05 m and thickness 0.033 mm. Table 3 shows the main technical characteristics of the packing tape, namely adherence, breaking load and elongation at break.

Analysis of the life cycle of this product involves consideration of all the inputs and outputs of five stages: (1) natural resources extraction, (2) manufacturing, (3) commercialization, (4) use and (5) end of life. The “use” stage is not considered here because all necessary resources have already been used, and any waste has yet to be generated.

The aim of inventory analysis is first to collect data, then to process these data to generate inventory analysis results. Software databases are normally used in LCA studies to collect inventory data, but sometimes, these data are time or geographically limited. The GaBi4.4® software has a large database and numerous processes modelled. PVC film or hydrocarbon resin manufacture processes are examples of processes modelled by the software. However, some processes were not modelled, and the following solutions were adopted for these processes not modelled by the software:

- Latex and natural rubber production: in this case, the process has been modelled according to the literature (Mohd 2009).
- Ink production: acetone, a standard organic solvent, was selected as the primary unique ink component. Ink quantities are minimal, and ink components other than acetone (e.g. metals) have not been considered.
- Electricity production: the printing company considered in this study is located in Navarre (Spain). As the Navarre Government recently reported, electric power was generated by natural gas combustion (25 %), hydroelectric power (25 %) and wind farms (50 %).

Table 1 Life cycle inventory software sources

Process	Source of LCI data
PVC film manufacture	PlasticsEurope (2011)
Kraft paper manufacture	BUWAL (2000)
PP film manufacture	PlasticsEurope (2011)
Hydrocarbon resin manufacture	PE International (2010)
Cardboard manufacture	BUWAL (2000)
Cardboard recycling	PE International (2010)
Truck transportation	PE International (2010)
Diesel generation	PE International (2010)
PVC, PP, Kraft paper, hydrocarbon resin, cardboard, municipal waste landfilling	BUWAL (2000)
PP, Kraft paper, hydrocarbon resin, cardboard, natural rubber incineration	PE International (2010)
Wind power, natural gas and hydropower	PE International (2010)

– Transportation: the large rolls of tape are bought as raw material to the printing company from Hernani (Basque Country, Spain, 120 km). This company obtained granulated PVC from Barcelona (Cataluña, Spain, 563 km). The boxes for the final printed plastic tape rolls are sold in Pamplona (Navarre, Spain, 40 km). Diesel trucks were used for transportation in all cases.
– End of life: primary application of packing tapes is corrugated cardboard closure. In Spain, 90 % of cardboard boxes packaging are recycled. Plastic tapes are removed from boxes in recycling plants or then separated as plastic residue (stickies) in the re-pulping stage on cardboard recycling plants. Strict plastic recycling of these residues would require a complex process to separate, clean and thicken them that likely makes it not economically viable. As a result, recycling and cardboard recycling plants usually landfill (50 %) and incinerate (50 %) these plastic residues (Jensen 1997). As PVC incineration is not recommended because of the risk of chlorinated toxic compounds being released to the atmosphere, PVC packing tapes were considered completely landfilled. The rest of the packing tape materials (ink and adhesive) were also considered landfilled. Gas production from landfill plants was thermally valorized to obtain power recycled to the printing process (Fig. 1, 1.28 kWh). Cardboard boxes and mandrels were assumed to be totally recycled to the packaging and commercialization stage.

2.3 Impact assessment

The goal of the life cycle impact assessment phase is to convert inventory results into impacts on the environment. The EII values for the life cycle stages of the PVC packing tape can be found in the electronic resources of this article. The software GaBi4.4® automatically completes the inventory analysis data transformation to EIIs by the characterization methods explained above.

2.4 Interpretation

The goal of the life cycle interpretation phase is to interpret overall results of the LCA and, more importantly, to identify environmentally significant issues from the life cycle impact assessment results (Wimmer et al. 2004).

Because the values for each EII are not comparable (EII values, Electronic Supplementary Material, Table S1), Fig. 2 shows a percentage representation where one column is the sum (100 %) of the equivalent unit of each EII. The percentages of each life cycle stage for one environmental impact index are represented in each column. For most EIIs, the life cycle stage with the highest contribution is the manufacture of the 10.5 large rolls of PVC plastic tape required to make the functional unit of printed tapes. The end-of-life stage represents an important contribution to the EP index because during PVC landfilling, plasticizers (phthalates), stabilizers and other organic additives leach out and increase the organic content of groundwater (Mersiowsky 2002; ARGUS 2000). Landfilling PVC also discharges small quantities of halogenated compounds (vinyl chloride) into the atmosphere which contribute to the ODP (ARGUS 2000). Finally, the

Table 2 PVC, Kraft paper and PP tape packing characteristics (small packing tape). ρ_{PVC}=1.42 g/cm^3, ρ_{Kraft}=0.64 g/cm^3, ρ_{PP}=0.85 g/cm^3. Adhesive: white (55 %$_w$ natural ribbon, 45 %$_w$ hydrocarbon resin)

	Thickness [μm]			Weight [g]		
	PVC	Kraft	PP	PVC	Kraft	PP
Support	33	70	28	309.3	291.1	157.1
Adhesive	17.3	40	16.5	103.0	238.1	98.2
Mandrel	–	–	–	29.4	29.4	29.4
Ink	–	–	–	3.8	3.8	3.8
Overall	50.3[a]	110[a]	44.5[a]	445.5	562.4	255.9

[a] Only thickness of the packing tape (without mandrel and ink)

Table 3 Technical packing tape information

	PVC	Kraft	PP
Adherence [N/cm]	2.4±0.5	8.5±3	1.9±0.5
Breaking load [N/cm]	47±12	45±15	42±13
Elongation at break [%]	60±20	7±3	100±40

printing stage contributes to the ODP with the emission of halogenated compounds during the manufacture of the cardboard mandrels. GaBi® databases for cardboard manufacture include halogenated organic emissions to the atmosphere derived from the bleaching process to decrease the brown colour of lignin and impurities. The transport and packaging stage contributes negatively because cardboard recycled from mandrel and boxes is introduced in this step. But, as it was mentioned before, the life cycle stage with the highest impacts is the manufacture of the large rolls of PVC plastic tape.

According to these results, it is reasonable to focus on the manufacture of the large tape rolls to reduce the environmental impact. Natural rubber, hydrocarbon resin, PVC film and cardboard manufacture are the processes that make up this stage (Fig. 1). Figure 3 shows the contribution of each process to the total values of the large tape roll manufacture environmental impact indexes (EII values, Electronic Supplementary Material, Table S2). PVC film manufacture is the process with the highest contribution to each EII, except for EP and ODP. Latex production during the natural rubber process releases phosphates (derived from fertilizers used during rubber cultivation) that contribute to the EP. Finally, the manufacture of synthetic resin during the production process represents a percentage in all the EII values due to its petrochemical origin. However, as previously mentioned, the PVC film manufacture process contributes the most to every other EII due to the high quantities used, their petrochemical origin and the use of chlorinated compounds in their manufacture.

Other important steps of the interpretation stage of LCA are the normalization and the weighting. ISO14044:2006 (ISO14044:2006) defines normalization as “calculation of the magnitude of indicator results relative to reference information”. The main aim of normalizing the category indicator results is to better understand the relative importance and magnitude of the results for each product system under study (Guinée 2002). In essence, normalization is a process dividing the EII of a given product by the normalization reference of the same impact category. The value of the normalized index represents the relative impact caused by the product to the total impact of the geographical region (Wimmer et al. 2004). One of the advantages of normalization is that it allows the conversion of the EIIs into equivalent and comparable magnitudes.

Table 4 shows the normalization factors for western European countries used in this work, and Table S3 in the Electronic Supplementary Material shows all the PVC packing tape life cycle normalized values. These are the result of multiplying EII values (Table S1, Electronic Supplementary Material) by their corresponding normalization factors. Table 4 shows that GWP, ADP fossil, FAETP and MAETP have low normalized factors, but their normalized environmental impacts are, with EP, the values with higher contribution to the total normalized life cycle impacts due to the high quantities of their respective equivalent units. The normalized value of GWP is 7.6 % of the overall normalized impacts, ADP_{fossil} 16.9 %, EP 17.5 %, FAETP 18.8 % and MAETP 22.2 %. The manufacturing process of large rolls of PVC tape is mainly responsible for normalized GWP, ADP fossil, FAETP and MAETP values, and the end-of-life stage is mainly responsible for the normalized EP value. As it was

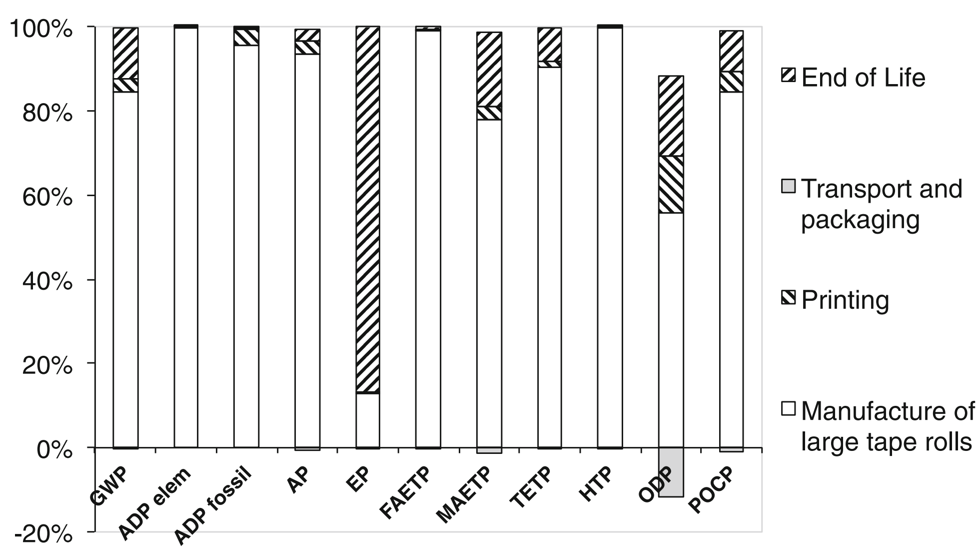


Fig. 2 Environmental impacts of PVC plastic tape packing life cycle steps

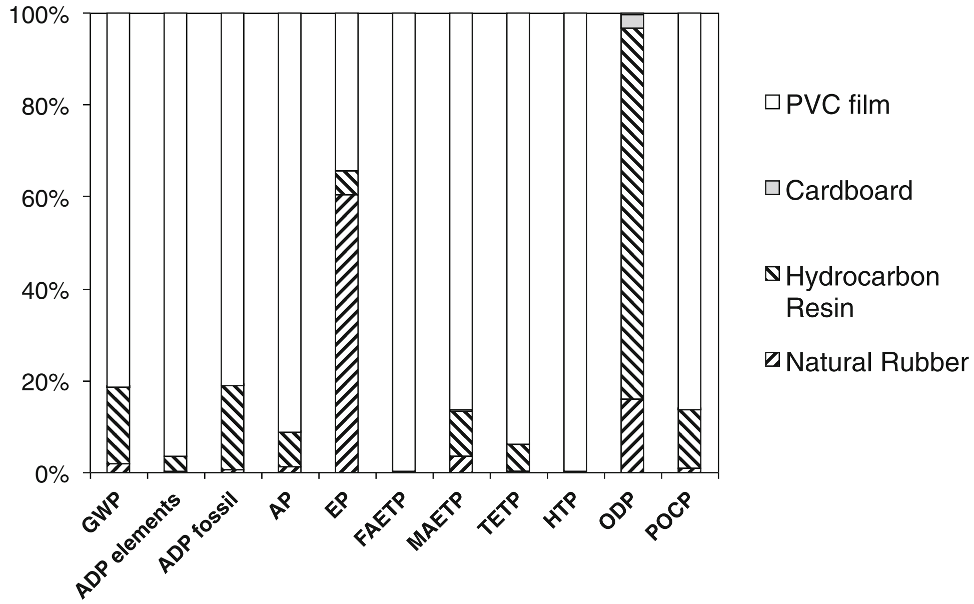


Fig. 3 Environmental impacts of the manufacture of large rolls of PVC tape

mentioned before, landfilling of PVC films causes these high EP values. As a result, the manufacture of large rolls of PVC packing tape contributes 77.5 % to the total normalized life cycle value, end-of-life stage 20.9 % and transport and printing stages with the remainder percentage. Figure 4 shows the sum of the normalized values of all the EIIs for each life cycle stage in equivalent units. The manufacture of the large rolls of plastic tape is clearly the life cycle stage with the highest normalized impact.

Table S4 in the Electronic Supplementary Material shows all the normalized values for the large rolls of tape from the PVC packing tape manufacture process. Obviously, normalized GWP, ADP fossil, FAETP and MAETP values are mainly responsible for the total normalized value. PVC film manufacture is the process with the highest contribution to these EEIs. The reason for the high FAETP and MAETP normalized values are the polychlorinated dioxins released to freshwater and hydrogen halides emitted to air. Polychlorinated dioxins are released during the oxychlorination process of PVC manufacture (ENDS 1995; Carroll et al. 2001). Hydrogen halide is released to the atmosphere in low quantities (Ostermayer and Giegrich 2006), but a high characterization factor is used to transform these quantities to equivalent units of the MAETP indicator (kilogram DCB eq.) due to the average oceanic residence time of this compound. However, there exists some controversy about this characterization factor, and this value has to be considered with care (Hans-Jörg et al. 2004). Fossil fuels used are the main reason of GWP and ADP fossil normalized values. Normalized values for the different processes that make up this manufacturing stage are also shown in Fig. 4. PVC film manufacture process has the highest values and is considered the most environmentally damaging process of the overall life cycle.

One implicit assumption of the normalization process is that the relative significance among the different impact categories is the same. In reality, this is not the case. The relative significance is also called weight, and the weighting in LCA means assigning relative significance to the impact categories based on social, ethical and politic values. When weight is multiplied by normalized impact, the result is called weighted impact. If all the impact categories are summed up, a single, unique weighted impact of a product is obtained. Table 5 shows the weighting factors that multiply the normalized EIIs as a result of evaluation by a panel of experts (Huppes and van Oers 2011). The overall weighted impact for the PVC life cycle is $7.9 \cdot 10^{-11}$ eq. units. This value is a relative measure of the environmental impact of a process, and it is going to become important in the next section when it will be compared with ecodesigned processes.

Finally, in order to better understand the significance, uncertainty and sensitivity of the life cycle impact assessment (LCIA), gravity, uncertainty and sensitivity analyses have been done (ISO14040:2006; ISO14044:2006). Gravity Analysis is a statistical procedure that identifies those data having the greatest contribution to the indicator result. For this analysis, EIIs with high normalization values have only been analysed because they indicate the processes with the highest environmental impacts (GWP, ADP fossil, EP, FAETP and MAETP). The PVC film manufacture process is mainly responsible for normalized GWP (69.2 %), ADP fossil (77.3 %), FAETP (98.8 %) and MAETP (69.1 %) values, and PVC film landfilling process for normalized EP value (85.0 %).

Uncertainty analysis is a procedure to determine how uncertainties in data and assumptions progress in the calculations and how they affect the reliability of the results of the

Table 4 Normalization factors for western European countries

	Normalization factor	Source
GWP	2.04E−13	Solomon et al. (2007)
ADP elements	1.22E−08	van Oers et al. (2002)
ADP fossil	3.23E−14	van Oers et al. (2002)
AP	3.70E−11	Huijbregts (1999b)
EP	7.69E−11	Heijungs et al. (1992)
FAETP	2.00E−12	Huijbregts (1999a), Huijbregts et al. (2001)
MAETP	9.09E−15	Huijbregts (1999a), Huijbregts et al. (2001)
TETP	2.13E−11	Heijungs et al. (1992)
HTP	1.32E−13	Huijbregts (1999a), Huijbregts et al. (2001)
ODP	1.15E−08	Daniel and Velders (2007)
POCP	1.22E−10	Derwent et al. (1998), Jenkin and Hayman (1999)

LCIA. Inventory data for latex and rubber production processes have been taken from literature and represent a source of uncertainty, but the contribution of this process to the overall normalized values of the different EEIs is, in all the cases, lower than 3 %; only for EP indicator is the contribution of this process 7.8 %. As a result, these data do not affect the reliability of the LCIA. Another uncertainty source may be the assumptions made concerning the end-of-life stage. It has been assumed that all PVC packing tape is landfilled. As mentioned in the Gravity Analysis, PVC film landfilled contributes 85.0 % to the overall normalized EP value, and assumptions made about the end-of-life process could be considered as a source of uncertainty. Because of this, a sensitivity analysis is necessary to determine the robustness of the results.

Sensitivity analysis allows determining how changes in data and methodological choices affect the results of the LCIA. Changes have been made with a different scenario assuming that 50 % of the PVC packing tapes at the end-of-life stage are incinerated and 50 % landfilled. A comparison of both scenarios shows that the overall GWP normalized value increases 31 % when incineration is included as end-of-life process, whereas the EP overall normalized value decreases 30 % due to the landfilling reduction; the rest of the indicators do not change. As a result, the overall weighted impact for the PVC packing tape life cycle only changes by 3.4 % compared with the original scenario. The sensitivity is lower than 10 % and can be considered not significant (Wimmer et al. 2004). In conclusion, the LCIA is robust, and assumptions regarding the end-of-life processes do not seem to be a source of significant uncertainties.

3 Reducing the environmental impact of packing tape manufacture through ecodesign

Taking into account the results of this study, it is clear that manufacturing packing tape using material other than PVC could reduce the overall environmental impact significantly. The company that supplies the large rolls of packing tape to the printing company also commercializes Kraft paper and polypropylene (PP) plastic packing tape. The main characteristics of these products are presented in Table 2, and the technical information appears in Table 3. The length and width dimensions of these types of tape are the same as that of PVC tape, 132 m and 50 mm, respectively, and the packing tape surface (functional unit) is the same, 1,663 m^2; however their support and adhesive thickness differ (Table 2). As packing tape is mainly used as a cardboard box closure system, it is reasonable to think that its correct performance will depend on the values of its technical characteristics (Table 3). Among them, breaking load is the characteristic that will mainly determine its right performance. In order to assure an equal and correct behaviour, it can be observed that

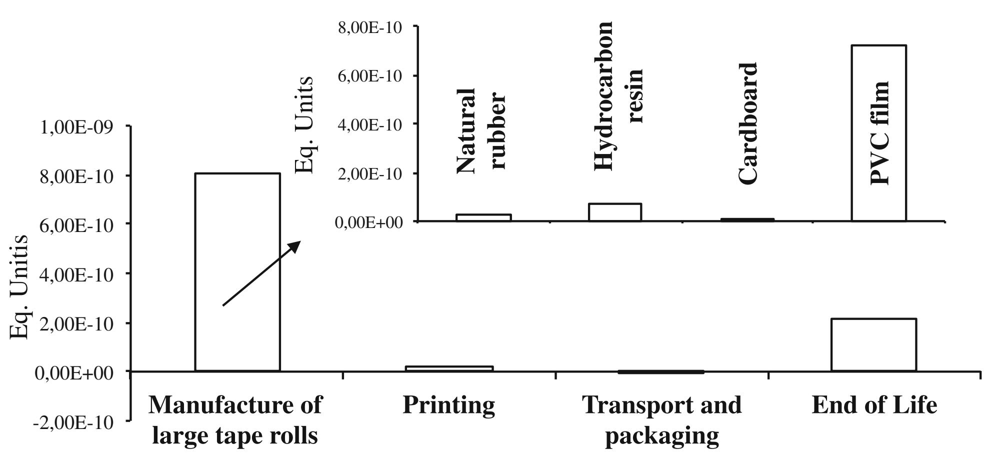


Fig. 4 Normalized EIIs for the PVC packing tape life cycle and the manufacture process of the large rolls of plastic tape

Table 5 Weighting factors for EU-27 countries (Huppes and van Oers 2011)

	Weighting factors
GWP	0.23
ADP elements	0.23/2
ADP fossil	0.23/2
AP	0.04
EP	0.07
FAETP	0
MAETP	0.03
TETP	0.11
HTP	0.2
ODP	0.04
POCP	0.05

different tape thicknesses are adjusted to keep constant their breaking loads at approximately around 45 N/cm. Elongation at break and adherence values differ depending on the material but in any case reach values that assure a correct performance (7±3 % and 1.9±0.5 N/cm elongation at break and adherence, respectively).

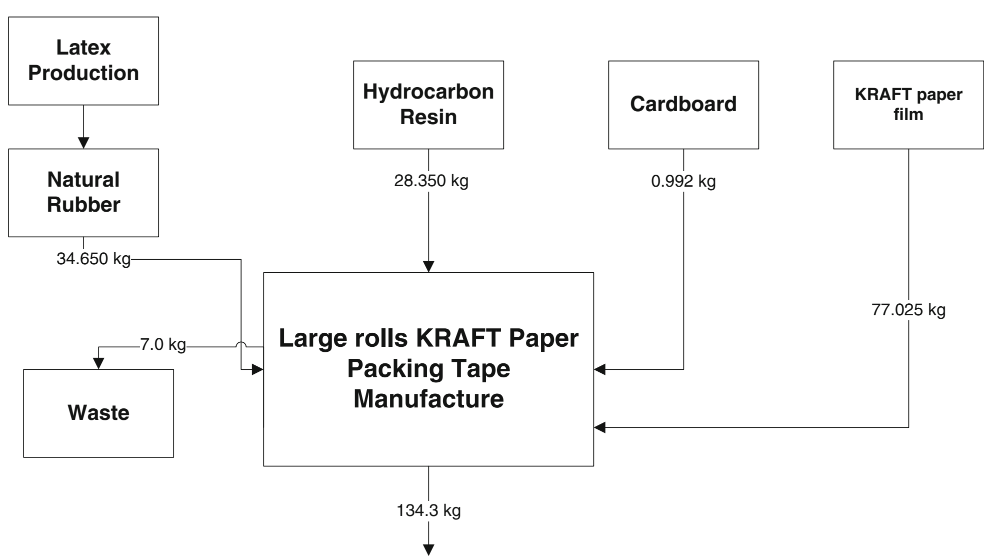
Life cycle assessments of Kraft paper and PP plastic packing tape have been performed and compared with the results obtained for PVC plastic packing tape to determine if the use of the former two products could reduce the environmental impacts. Systems shall be compared using the same functional unit and equivalent methodological considerations (ISO14044:2006). The functional unit of 1,663 m^2 of packing tape surface and the function of the product were the same for the three studies.

Figures 5 and 6 show the flow chart of the manufacture processes for 10.5 large rolls of Kraft paper and PP plastic tape calculated with these dimensions. Due to the different thickness and density of the support material (PVC, Kraft paper and PP), adhesive and support contents material are also different.

Regarding life cycle, Kraft paper and PP plastic packing tape have stages similar to those of PVC plastic packing tape, differing only in the manufacture and end-of-life processes. In relation to end-of-life cycles, and as has been said for PVC films, Kraft paper and PP plastic packing tape recycling would require a complex process that makes it not economically viable. Recycling and cardboard recycling plants usually landfill (50 %) or incinerate (50 %) these packing tape residues from cardboard boxes (Jensen 1997). Landfilling was used as the unique end-of-life process for PVC packing tape because of the highly toxic compound formation during incineration, but for Kraft and PP tapes, incineration is going to be considered as important as landfilling (50 % of the packing tapes will be incinerated and 50 % landfilled). Energy obtained during end-of-life processes (11.3 kWh, Kraft paper; 18.2 kWh, PP) has been recycled and used as primary energy in the printing stage.

EII values for the life cycle of Kraft packing tape are presented in Table S5 in Electronic Resources. Figure 7 shows the variation in selected EIIs (with higher normalized values) and the percentage of reduction with respect to PVC film. Kraft paper packing tape reduces all the selected EIIs, except GWP. Kraft paper film and PVC film masses are very similar; however, comparing the EIIs of producing 1 kg of Kraft paper to those of producing 1 kg of PVC (data not shown), it can be seen that all the EIIs other than ODP decrease, especially toxicity indicators and GWP and ADP indexes (ODP indicator increases because during Kraft paper production, Halon 1301 is released to the atmosphere. The ozone-depleting gas Halon 1301 is emitted during pesticide production used in Kraft paper manufacture (Hauschild and

Fig. 5 Flowchart of the large Kraft paper packing tape manufacturing process



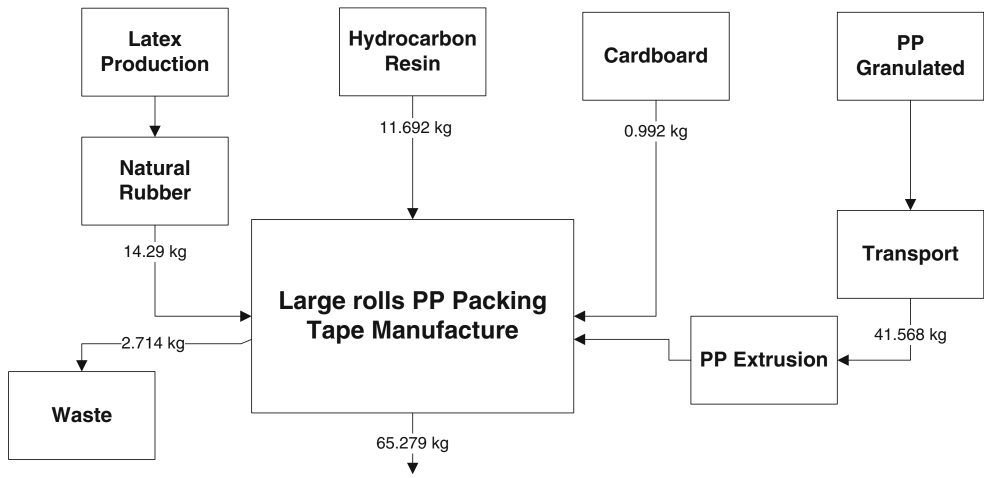


Fig. 6 Flowchart of the large PP plastic packing tape process manufacturing process

Wenzel 1998; Afrane and Ntiamoah 2011)). Nevertheless, large rolls of Kraft paper tape contain greater quantities of adhesive, resulting in a lesser decrease in environmental impact than might otherwise be expected. Table S6 in the Electronic Supplementary Material shows EII values for the large Kraft roll packing tape manufacture. Natural rubber and hydrocarbon resin make up the adhesive; Kraft paper film has 28.3 g of hydrocarbon resin (Fig. 5), and PVC film has only 12.3 g of this material (Fig. 1). High quantities of CO_2 are released to the atmosphere during synthetic resin manufacture, and this causes the total GWP indicator to increase 21.9 %. ADP fossil is reduced because less fossil resources are necessary to produce Kraft film. EP indicator decreases 68.6 % because Kraft film does not contain plasticizers. Finally, FAETP and MAETP indicators are reduced because halogenated compounds are not released during Kraft film manufacture.

PP film reduces all the selected EIIs with respect to PVC film. There are two main reasons for these drops: first, large rolls of PP packing tape are lighter than PVC tape due to their lower density and reduced film thickness, which implies less mass of PP to produce the tapes (81.8 kg of PVC film versus 41.6 kg of PP film), and second, the PP film manufacture process is less environmentally damaging than the PVC

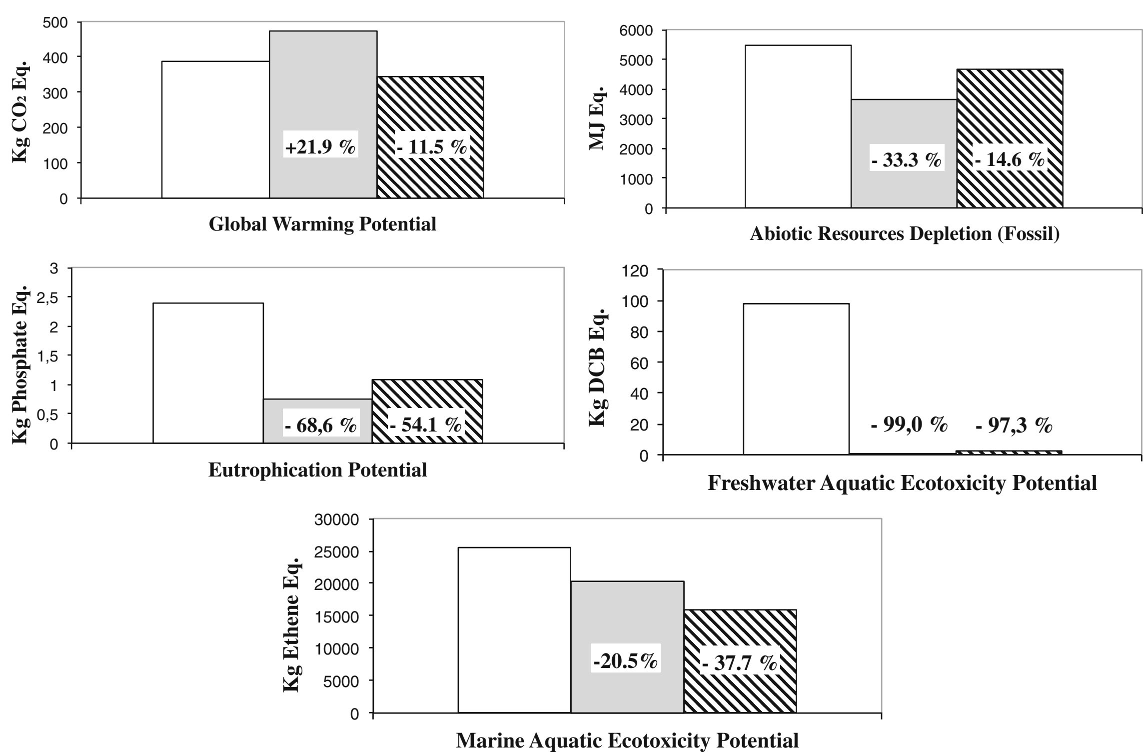


Fig. 7 Comparison between the sum of selected EIIs for the PVC (*white*), Kraft paper (*grey*) and PP (*lined*) overall life cycles

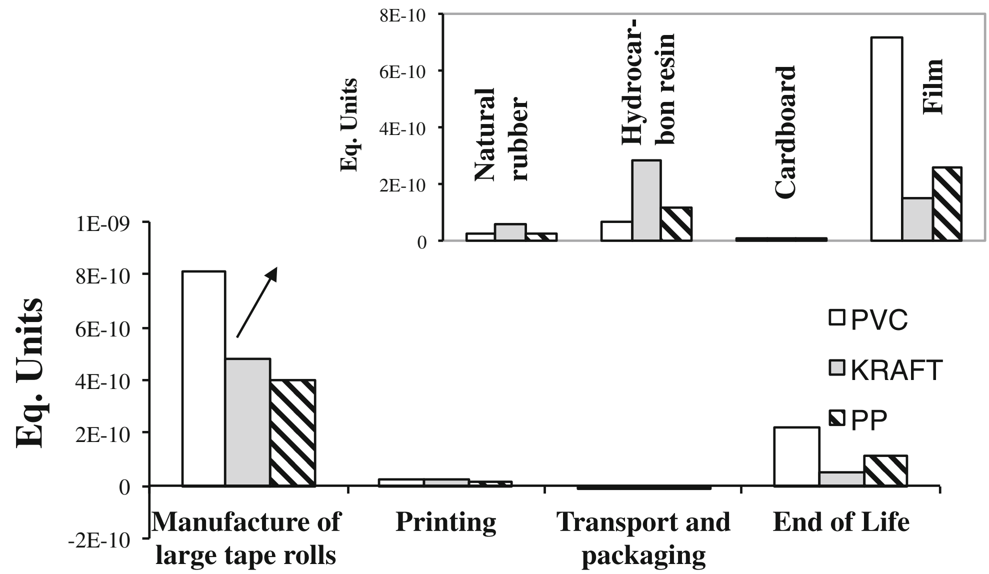


Fig. 8 Normalized EIIs for the PVC, Kraft paper and PP life cycles and manufacture process of the 10.5 large rolls of tape

process. Comparing the EIIs (data not shown) of producing 1 kg of PVC and 1 kg of PP film, it can be observed that PVC film production increases all toxicity indicators due to the emissions of halogenated organic compounds into the air and water. Adhesive masses are very similar for both types of plastic tape.

Normalized impacts of the life cycles of the three types of packing tape are presented in Fig. 8 (all values are presented in Tables S9 and S10 in the Electronic Supplementary Material). Manufacture of the large tape rolls and end of life are the only remarkable stages as shown by the normalized EIIs. Using Kraft support reduces the manufacture stage impact because its production has less impact than the production of PVC granules and reduces the end-of-life stage impact because Kraft paper is a biodegradable material. PP produces a remarkable reduction in the normalized impact of the large tape roll manufacture due to the reasons mentioned above. Regarding end-of-life stage, landfilling has been combined with incineration, and as a result, eutrophication, mainly responsible of plastics end-of-life impact, is reduced. Because of this, the end-of-life PP process impact is reduced compared with PVC.

As the manufacture of the large tape rolls has the highest impacts, Fig. 8 also presents the normalized impacts for the overall manufacture process (Tables S11 and S12 in the Electronic Supplementary Material). The Kraft manufacture process has smaller normalized values, showing that Kraft paper production has less environmental impact than production of granulated PVC. However, Kraft paper packing tapes have more adhesive than PVC and PP films, and the impact of hydrocarbon resin and natural rubber manufacture is higher. PP film production is also less environmentally damaging than PVC film production. PP packing tapes have similar quantities of adhesive than PVC, but fewer than Kraft, and as a result, the compared overall impact of generating large tape rolls is PVC>Kraft>PP.

Figure 9 shows a comparison between the weighted factor sums of the life cycles of the three types of materials. It can be seen that Kraft paper and PP plastic packing tape both

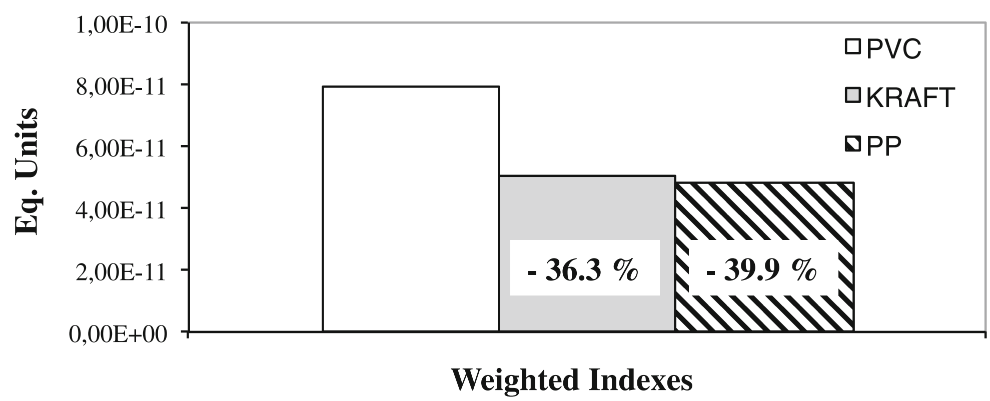


Fig. 9 Sum of weighted EIIs for the PVC, Kraft paper and PP life cycles

reduce the overall weighted factor relative to the PVC system (36.3 and 39.9 %, respectively).

4 Conclusions

Although there exist some studies about environmental impact of packing tapes, they only focused on the end-of-life cycle stage and concluded that PSA plastic packing tapes are the best option because these materials do not cause problems in cardboard box recycling and could be separated from the boxes and finally landfilled or thermally treated.

The main objective of ecodesign is to reduce waste and raw material use of a product through good initial design. Good design requires quantification of the environmental impacts of all the life cycle stages of a product to reduce the effects of the stage with the highest impact. In this study, life cycle assessment has been used to determine the PVC packing tape life cycle stage with the highest environmental impact. Results show this stage to be the manufacture of the large rolls of plastic tape necessary to produce the final printed plastic tape product, with the production of the PVC film contributing most to the impact value.

With these results, it is reasonable to assume that the use of different material packing tapes could reduce the value of the stage with highest environmental impact (manufacture of 10.5 large rolls of tape). The supplier that provides PVC also commercializes Kraft paper and PP plastic packing tape, and therefore, LCA has been used in order to assess if the use of these types of tape would result in smaller environmental impacts. The functional unit of 1,663 m^2 of packing tape surface and the function of the product are the same for the three studies. Kraft paper production is not as environmentally harmful as the production of PVC granules; however, the quantities of adhesive present in this type of tape are higher than those of PVC tape, resulting in a less pronounced decrease in overall environmental impact. PP plastic packing tape has less thickness than PVC tape, and granulated PP material production is less environmentally harmful than the production of granulated PVC. These facts result in smaller EII values for PP plastic tape than for PVC. The use of PP plastic and Kraft paper packing tape also reduces the normalized environmental impacts of the life cycle stages. The weighted impacts of Kraft paper and PP plastic packing tape life cycle are reduced by 36.3 and 39.9 %, respectively. These results have been normalized for a region of western Europe where some EIIs have been prioritized over others (e.g. marine ecotoxicity over global warming potential) and have been weighed by a panel of experts following economic, social and political standards.

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